Low mass dilepton production at High p_T

Jianwei Qiu
Brookhaven National Laboratory

Based on work with Kang and Vogelsang, **arXiv:0811.3662** (PRD), **arXiv:0907.4498** (NPA)

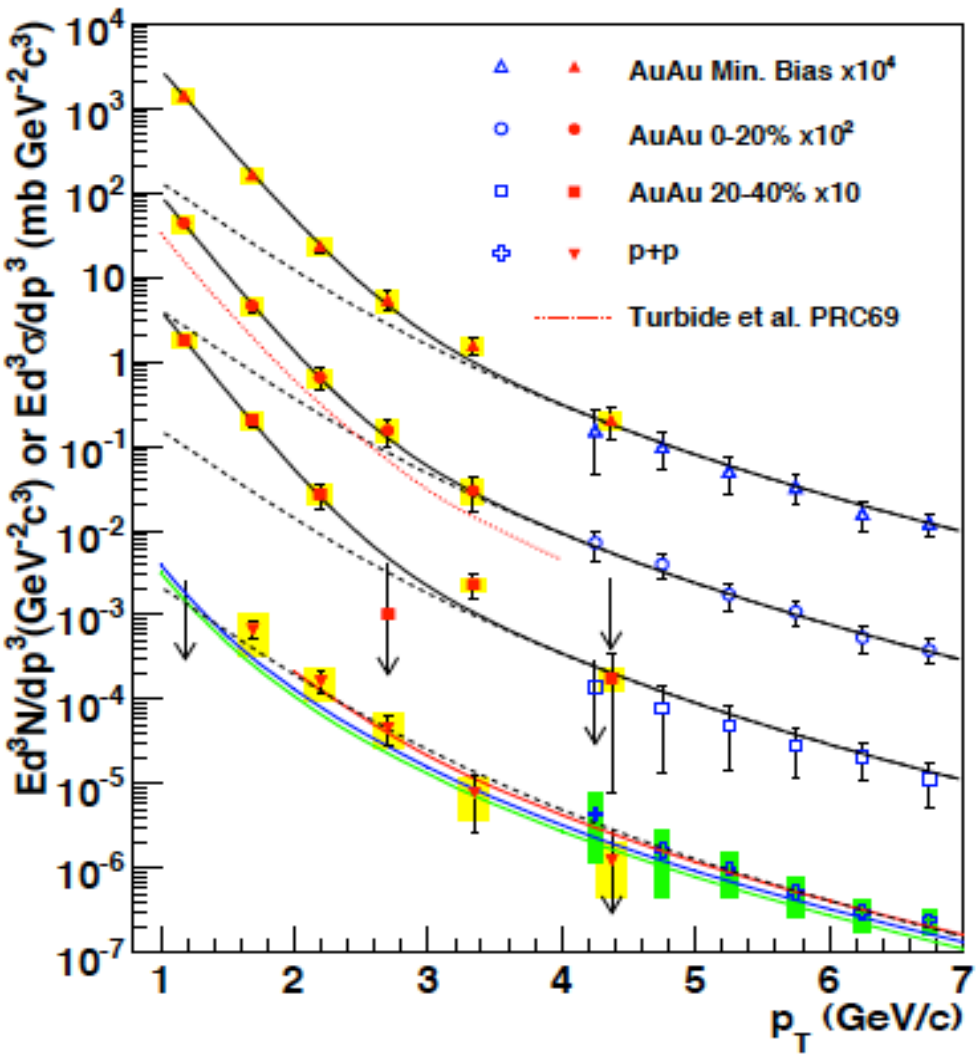
RBRC Workshop on "Progress in High p_T Physics at RHIC"
RIKEN/BNL Research Center (RBRC), BNL, Upton, NY 11973

Outline

- ❑ PHENIX Measurement of low mass dileptons
  - – Temperature of sQGP in central Au-Au collisions
- ❑ QCD calculation for low mass dilepton production in hadronic collisions
  - – pQCD factorization works as good as that for direct photon production at high pT
- ❑ Partonic multiple scattering in nuclear medium enhances the production rate of low mass dileptons
  - – Opposite sign to that in DIS
- ❑ Summary and out look

The PHENIX measurement

- Low mass e^+e^- pairs ➡ direct photon production:



arXiv:0804.4168 (PRL in press)

$$\frac{d^2 n_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right) S dn_\gamma$$

S : process dependent factor

$$\sqrt{s} = 200 \text{ GeV}$$

$$m_{ee} < 0.3 \text{ GeV}/c$$

$$1 < p_T < 5 \text{ GeV}/c$$

Difference pp vs AA
– exponential

➡ Temperature

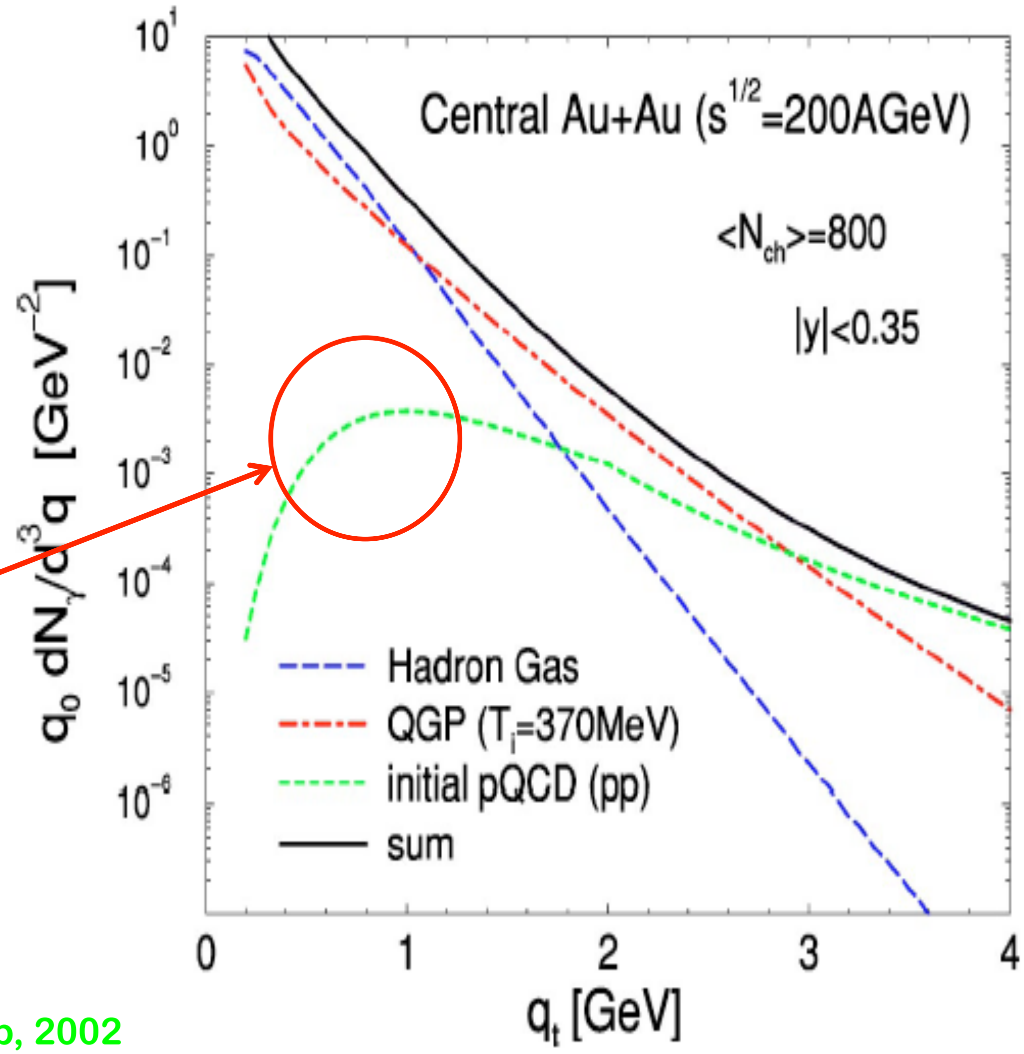
$$T = 221 \pm 19^{\mathrm{stat}} \pm 19^{\mathrm{syst}} \text{ MeV}$$

Hadronic production of thermal photons

- Photons from various sources:

Turbide, Rapp, Gale, PRC 2004

$$q_0 \frac{dR_\gamma}{d^3q} = \int \frac{d^3p_1}{2(2\pi)^3E_1} \frac{d^3p_2}{2(2\pi)^3E_2} \frac{d^3p_3}{2(2\pi)^3E_3} \times (2\pi)^4 \delta^{(4)}(p_1 + p_2 \to p_3 + q) \times |\mathcal{M}|^2 \frac{f(E_1)f(E_2)[1 \pm f(E_3)]}{2(2\pi)^3}$$



Rate for pp collision

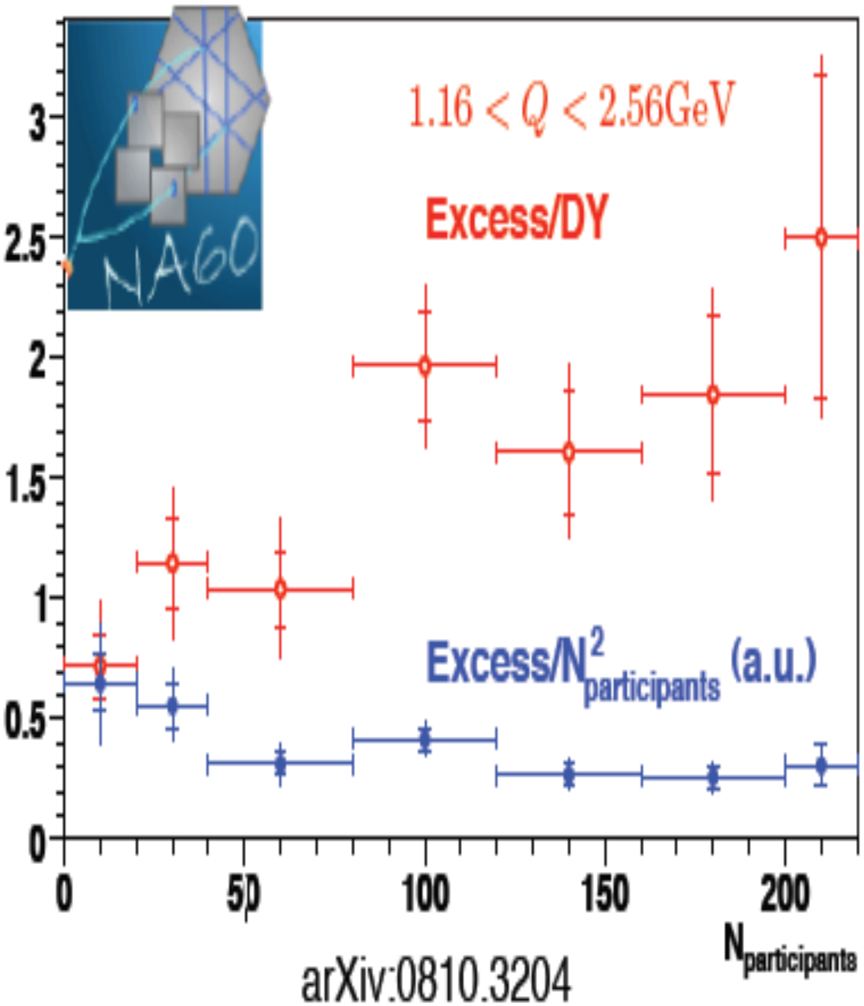
$$q_0 \frac{d^3\sigma_\gamma^{pp}}{d^3q} = 6495 \frac{\sqrt{s}}{(q_t)^5} \frac{\text{pb}}{\text{GeV}^2}$$

for $\sqrt{s} = 200$ GeV, $q_T \leq 10$ GeV

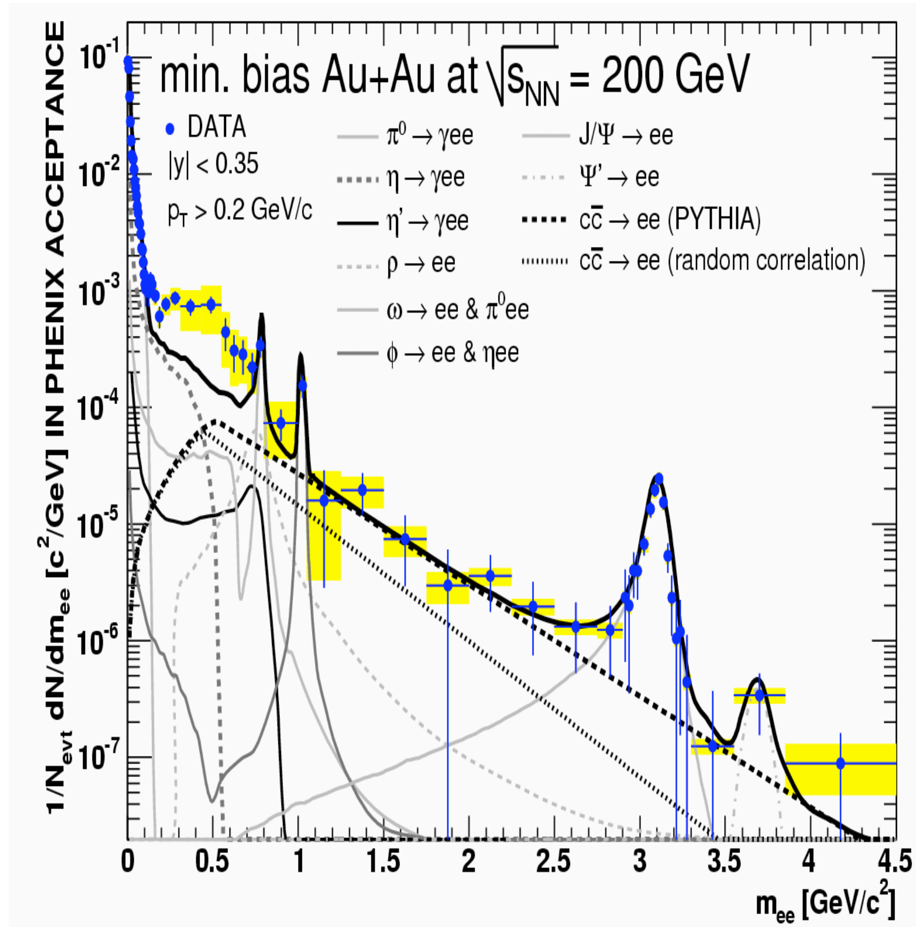
Rapp, 2002

The enhancement also seen in total rate

❑ Fixed target:



❑ Collider:



PHENIX

Questions

How reliable we can calculate the production rate of low mass lepton pairs in hadronic collisions?

Process: $A(p_1) + B(p_2) \to \ell^+\ell^-(Q) + X$

Kinematics: $Q_T^2 \gg Q^2$

"Drell-Yan" – like process:

$$Q_T^2 \gg Q^2 \gg \Lambda_{\mathrm{QCD}}^2$$

Clean process for extracting the gluon distribution

Berger, Gordon, Klasen, 1998
Qiu, Zhang, 2001
Berger, Qiu, Zhang, 2002

"Direct photon" – like process:

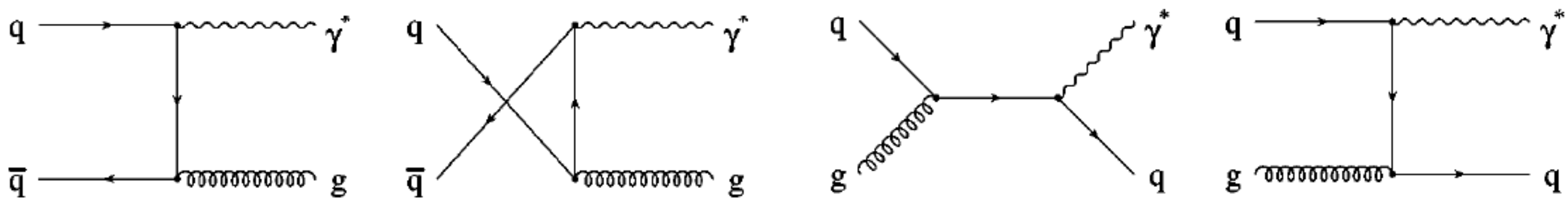
$$Q_T^2 \gg Q^2 \sim \Lambda_{\mathrm{QCD}}^2$$

QCD factorization is as good as that for high p_T direct photon production

Kang, Qiu, Vogelsang, 2009

Lepton pair production at high p_T

❑ Clean probe of gluon without final-state interaction



- Compton subprocess gives a small negative contribution to inclusive Drell-Yan lepton pair production
- It dominates the transverse momentum distribution when $Q_T > \frac{Q}{2}$

❑ Complementary to prompt photon – m << Q:

$$\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{dQ^2\, dQ_T^2\, dy} = \left(\frac{\alpha_{\rm em}}{3\pi Q^2}\right) \frac{d\sigma_{AB\to\gamma^*(Q)X}}{dQ_T^2\, dy}$$

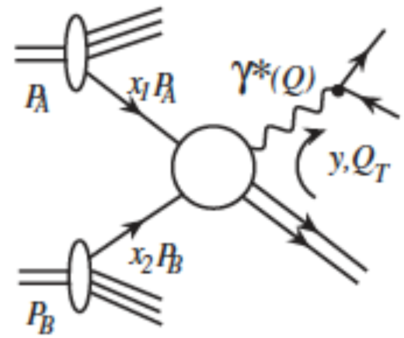
$$\boxed{\frac{10^{-3}}{Q^2}}$$

❑ But, the rate is lower!

Idea: Lower Q, not too small Q_T

QCD factorization for Drell-Yan

- QCD factorization is valid when $Q,\, Q_T \gg \Lambda^2_{\rm QCD}$:
  - – separation of momentum scales
  - – photon is produced at $t_\gamma \sim 1/Q \ll$ fm
  - – inclusive lepton pair production

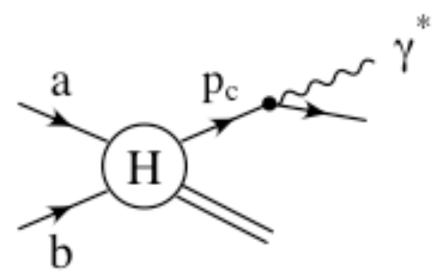


$$\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{dQ^2\,dQ_T^2\,dy} = \left(\frac{\alpha_{\rm em}}{3\pi Q^2}\right)\sqrt{1-\frac{4m_\ell^2}{Q^2}}\left(1+\frac{2m_\ell^2}{Q^2}\right)\frac{d\sigma_{AB\to\gamma^*(Q)X}}{dQ_T^2\,dy}$$

Power series of α_s

$$\frac{d\sigma_{AB\to\gamma^*(Q)X}}{dQ_T^2\,dy} = \sum_{a,b}\int dx_1 f_a^A(x_1,\mu)\int dx_2 f_b^B(x_2,\mu)\,\frac{d\hat\sigma^{\rm Pert}_{ab\to\gamma^*(Q)X}}{dQ_T^2\,dy}(x_1,x_2,Q,Q_T,y;\mu),$$

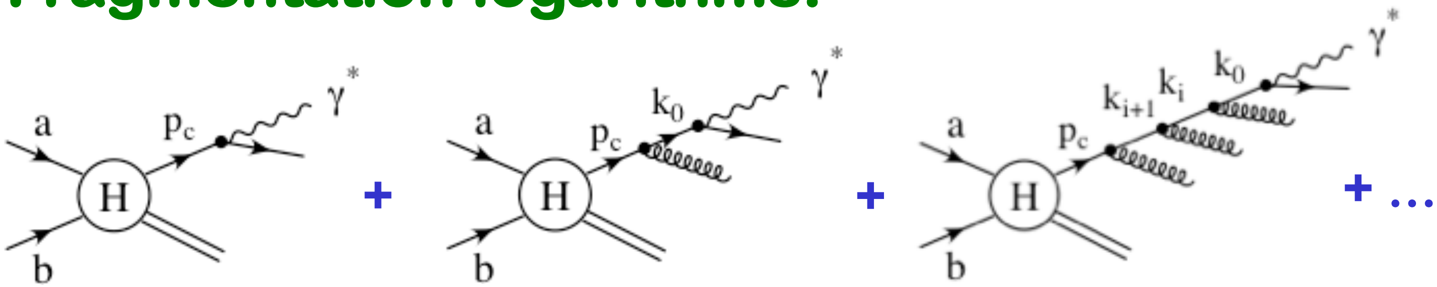
- QCD factorization is valid even if $Q_T^2 \gg Q^2 \gg \Lambda^2_{\rm QCD}$:
  - – photon is produced at $t_\gamma \sim 1/Q \gg 1/Q_T$
  - – large logarithms: $\alpha_s(Q)^*\log(Q_T/Q)$
  - – **resummation/reorganization**



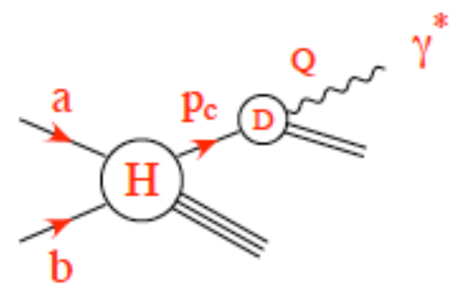
Resummation of fragmentation logarithms

❑ Fragmentation logarithms:

Qiu, Zhang, 2001, Berger, Qiu, Zhang 2002



❑ Resummation/reorganization:



$$\mu_F^2 \frac{d}{d\mu_F^2} D_{c\to\gamma^*}(z,\mu_F^2;Q^2)\Big| = \left(\frac{\alpha_{em}}{2\pi}\right)\gamma_{c\to\gamma^*}(z,\mu_F^2,\alpha_s;Q^2) + \left(\frac{\alpha_s}{2\pi}\right)\sum_d \int_z^1 \frac{dz'}{z'} P_{c\to d}\left(\frac{z}{z'},\alpha_s\right) D_{d\to\gamma^*}(z',\mu_F^2;Q^2)$$

❑ Cross section:

All logarithms!

$$\frac{d\hat{\sigma}^{\text{Pert}}_{ab\to\gamma^*(Q)X}}{dQ_T^2\,dy} = \frac{d\hat{\sigma}^{\text{Dir}}_{ab\to\gamma^*(Q)X}}{dQ_T^2\,dy} + \frac{d\hat{\sigma}^{\text{Frag}}_{ab\to\gamma^*(Q)X}}{dQ_T^2\,dy}$$

No logs!

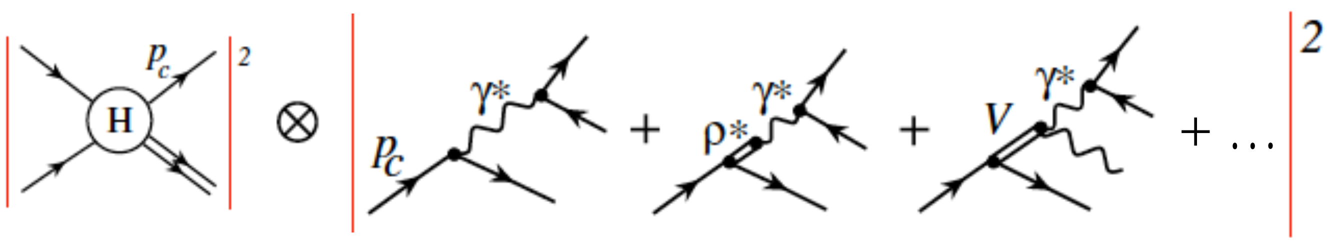
$$\frac{d\hat{\sigma}_{ab\to cX}}{dp_{c_T}^2\,dy} \otimes D_{c\to\gamma^* X}$$

Input fragmentation functions

- **"Drell-Yan" – like process** $Q_T^2 \gg Q^2 \gg \Lambda_{\rm QCD}^2$ **:** Berger, Qiu, Zhang 2002
  - lepton pair is mainly from decay of a virtual photon of mass Q
  - $Q(\gg \Lambda_{\rm QCD})$ is a natural regulator for the fragmentation logs
  - Input fragmentation functions are purely perturbative
- **"Direct photon" – like process** $Q_T^2 \gg Q^2 \sim \Lambda_{\rm QCD}^2$ **:**

Kang, Qiu, Vogelsang 2009

  - $Q_T(\gg \Lambda_{\rm QCD})$ is a perturbative scale, but $Q(\sim \Lambda_{\rm QCD})$ is not
  - the lepton pair can be produced non-perturbatively



$$D_{f\to\gamma^*}(z,\mu_0^2;Q^2) \equiv D^{\rm QED}_{f\to\gamma^*}(z,\mu_0^2;Q^2) + D^{\rm Nonpert}_{f\to\gamma^*}(z,\mu_0^2;Q^2)$$

Model the input fragmentation functions

- **Extract the input fragmentation functions from data:**
  - input fragmentation functions are process independent
  - "derive" or "model" the functional form of the distributions
  - fix all unknown parameters by fitting available data
- **Our model:**
  - "QED" part:

$$D^{\mathrm{QED}(0)}_{q\to\gamma^*}(z,\mu_0^2;Q^2)=e_q^2\left(\frac{\alpha_{\mathrm{em}}}{2\pi}\right)\left[\left(\frac{1+(1-z)^2}{z}\right)\ln\left(\frac{\mu_0^2}{Q^2/z+\lambda^2}\right)-\left(\frac{Q^2}{Q^2/z+\lambda^2}-\frac{Q^2}{\mu_0^2}\right)\right],$$

$$D^{\mathrm{QED}(0)}_{\bar{q}\to\gamma^*}(z,\mu_0^2;Q^2)=D^{\mathrm{QED}(0)}_{q\to\gamma^*}(z,\mu_0^2;Q^2),\quad D^{\mathrm{QED}(0)}_{g\to\gamma^*}(z,\mu_0^2;Q^2)=0.$$

  - "hadronic" part:

$$D^{\mathrm{Nonpert}}_{q\to\gamma^*}(z,\mu_0^2;Q^2)\equiv\kappa D_{q\to V}(z,\mu_0^2)\,\frac{4\pi\alpha_{\mathrm{em}}}{f_V^2}\left(1-\frac{Q^2}{m_V^2}\right)^3$$

Further assume: $m_V=m_\rho,\ f_\rho^2/4\pi=2.2$, and $D_{f\to V}\approx D_{f\to\pi}$

  - fitting parameters: $\lambda(>\Lambda_{\mathrm{QCD}}),\ \kappa(\sim 1)$

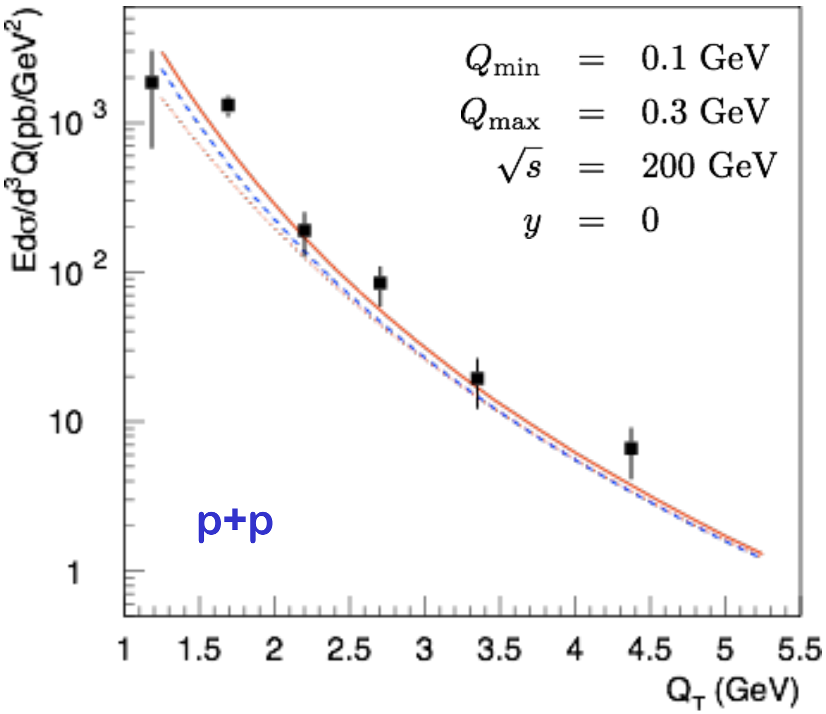
Invariant Cross Section

Kang, Qiu, Vogelsang, PRD 2009

❑ Definition:

$$E\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{d^3Q} \equiv \int_{Q^2_{\rm min}}^{Q^2_{\rm max}} dQ^2\,\frac{1}{\pi}\,\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{dQ^2\,dQ_T^2\,dy}$$

❑ Role of non-perturbative fragmentation function:



Data from PHENIX: arXiv:0804.4168

- **Input FF:**

  $$D(z,\mu_0) = D^{\rm QED}(z) + \kappa\, D^{\rm NP}(z)$$

- **QED alone (dotted):**

  $\kappa = 0$ at $\mu_0 = 1$ GeV

- **QED + hadronic input (solid):**

  $\kappa = 1$ at $\mu_0 = 1$ GeV

Hadronic component of fragmentation is very important at low Q_T

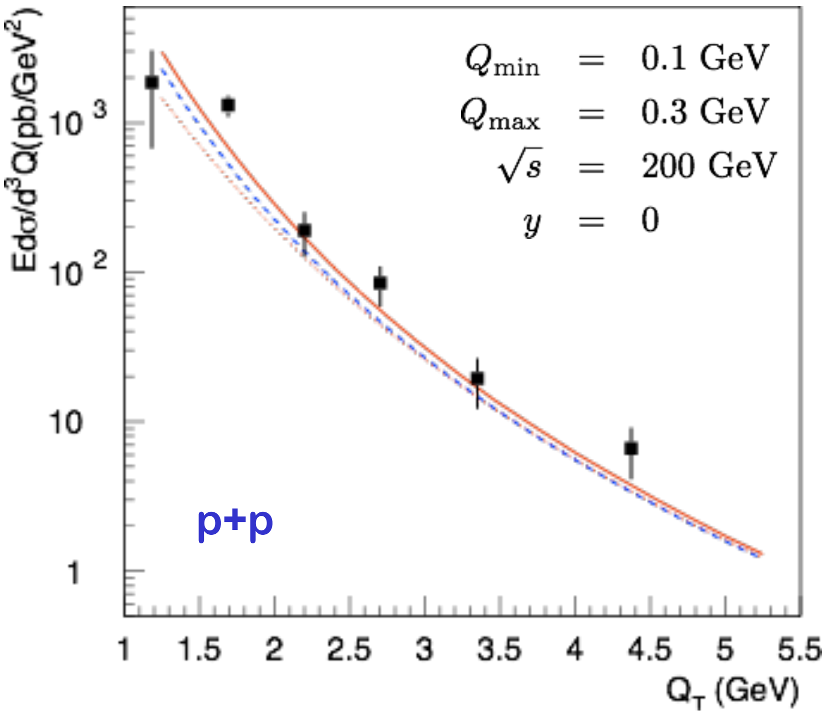
"Direct photon" approximation

❑ **Dilepton production vs direct photon production:**

$$E\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{d^3Q} \approx \frac{d\sigma_{AB\to\gamma(\hat{Q})X}}{dQ_T^2dy}\int_{Q^2_{\min}}^{Q^2_{\max}} dQ^2\left(\frac{\alpha_{em}}{3\pi^2 Q^2}\right)\sqrt{1-\frac{4m_\ell^2}{Q^2}}\left(1+\frac{2m_\ell^2}{Q^2}\right)$$

$$\approx \frac{\alpha_{em}}{3\pi}\ln\left(\frac{Q^2_{\max}}{Q^2_{\min}}\right)E_\gamma\frac{d\sigma_{AB\to\gamma(\hat{Q})X}}{d^3Q}$$

Direct photon cross section



Data from PHENIX: arXiv:0804.4168

❖ **Inclusive NLO direct photon (blue-dashed)**

Gordon, Vogelsang, 1993

❖ **Direct photon code has similar non-perturbative fragmentation functions**

Nuclear dependence

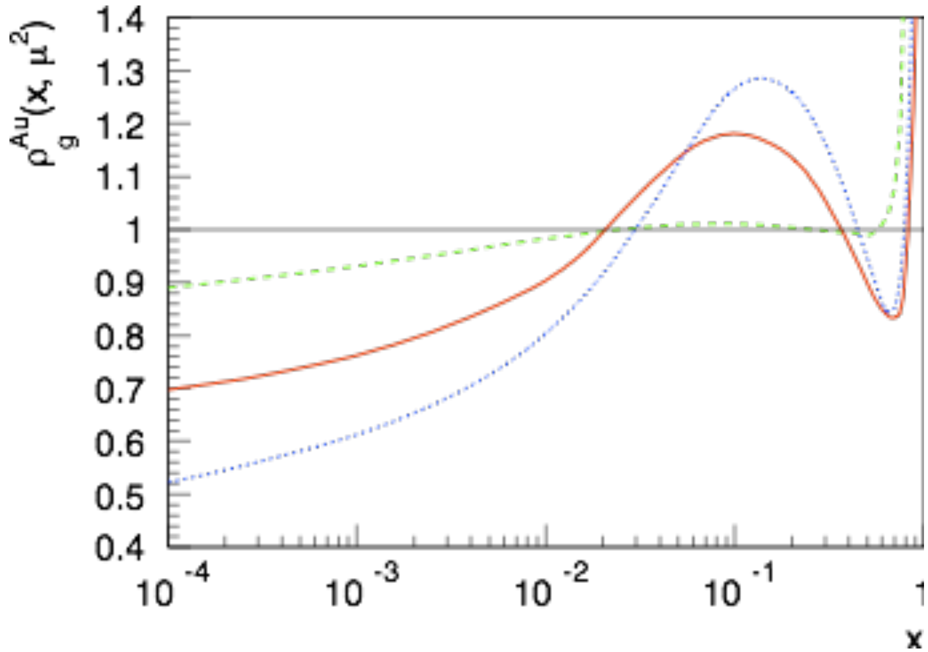
- In a gas target:
  - Nucleons have a large empty space between them
  - They are quantum mechanically incoherent for the short-range strong interaction
- In a nuclear target:
  - Nucleons are very close to each other – partonic rescattering
  - They are quantum mechanically coherent
  - The hard probe is not necessarily "local" – small x
- Magic of heavy ion beams:
  - Very large hadronic total cross section
  - Hot medium produced from the interaction between colors (soft gluons) of colliding ions

Modern nuclear parton distributions

- Definition:

$$f_i^{p/A}(x,\mu^2) \equiv \rho_i^A(x,\mu^2)\, f_i^p(x,\mu^2)$$

- Three sets nuclear gluon distribution for A=197:



Solid: EKS98

Dashed: FS2003

Dotted: EPS08

All nPDFs fit existing data!

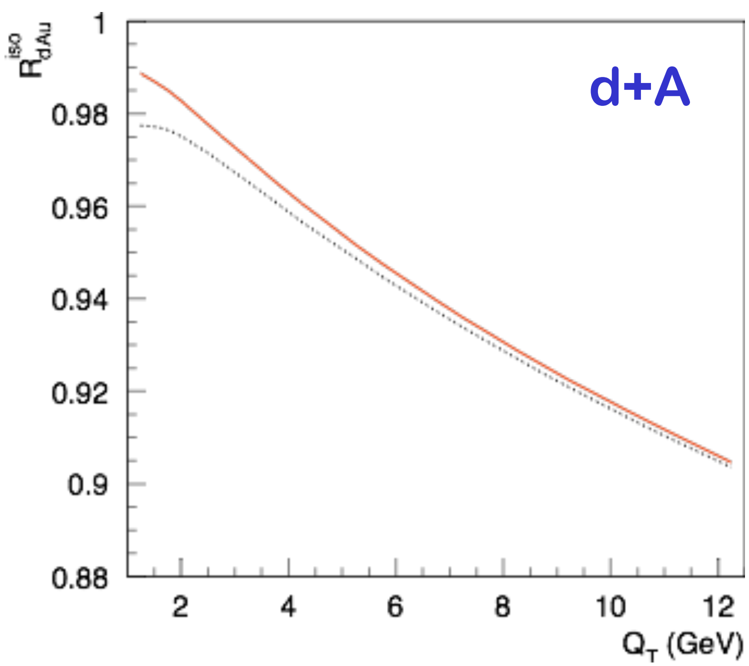
Isospin effect in nuclear collisions

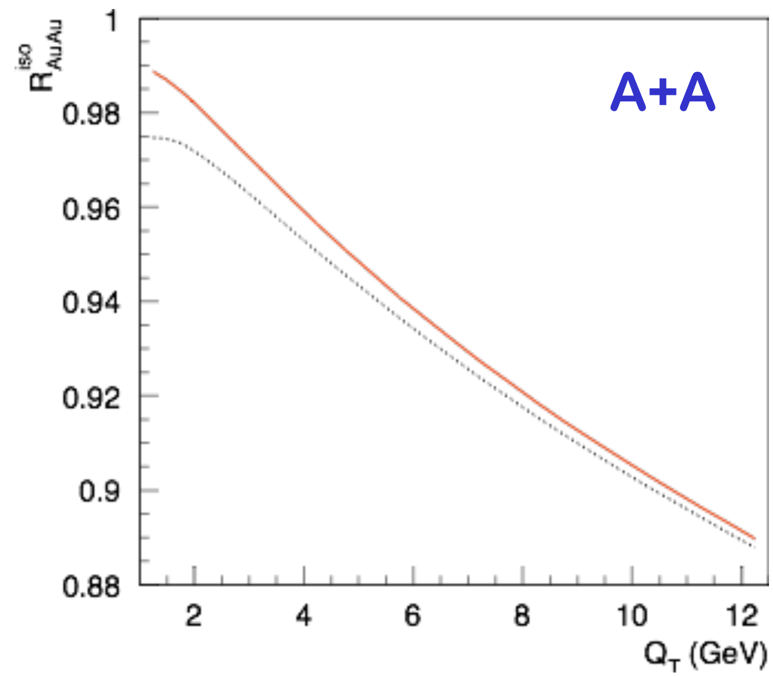
❑ **Definition:**

$$R^{\rm iso}_{\rm dAu} \equiv \frac{\frac{1}{2A} d^2\sigma^{\rm dAu}/dQ_T dy}{d^2\sigma^{pp}/dQ_T dy}$$

$$f_i^p(x,Q^2) \to \left[Z\cdot f_i^p + (A-Z)\cdot f_i^n\right]/A \qquad i = q, \bar{q}, g$$

❑ **Strong isospin effect:**





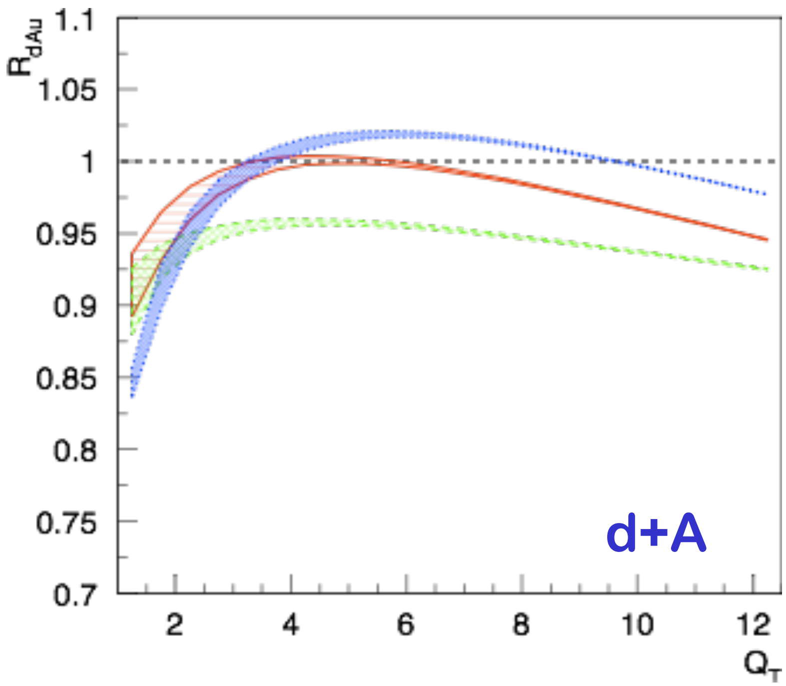
$$\sigma_{qg} \propto \frac{4}{9}f_u^n + \frac{1}{9}f_d^n = \frac{4}{9}f_d^p + \frac{1}{9}f_u^p \qquad f_u^p > f_d^p \quad \Longrightarrow \quad \sigma^{nn} < \sigma^{np} = \sigma^{pn} < \sigma^{pp}$$

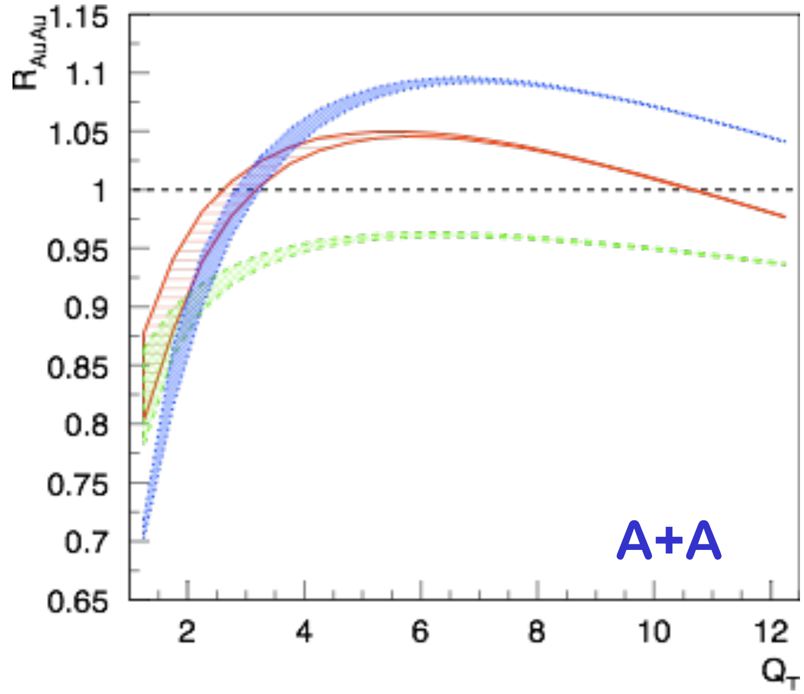
Sensitivity on gluon distribution

- **Nuclear modification factor:**

$$R_{\mathrm{dAu}} \equiv \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N^{\mathrm{dAu}}/dQ_T dy}{d^2 N^{pp}/dQ_T dy} \overset{\mathrm{min.bias}}{=} \frac{\frac{1}{2A} d^2 \sigma^{\mathrm{dAu}}/dQ_T dy}{d^2 \sigma^{pp}/dQ_T dy}$$

- **RHIC kinematics – if dominated by single scattering:**

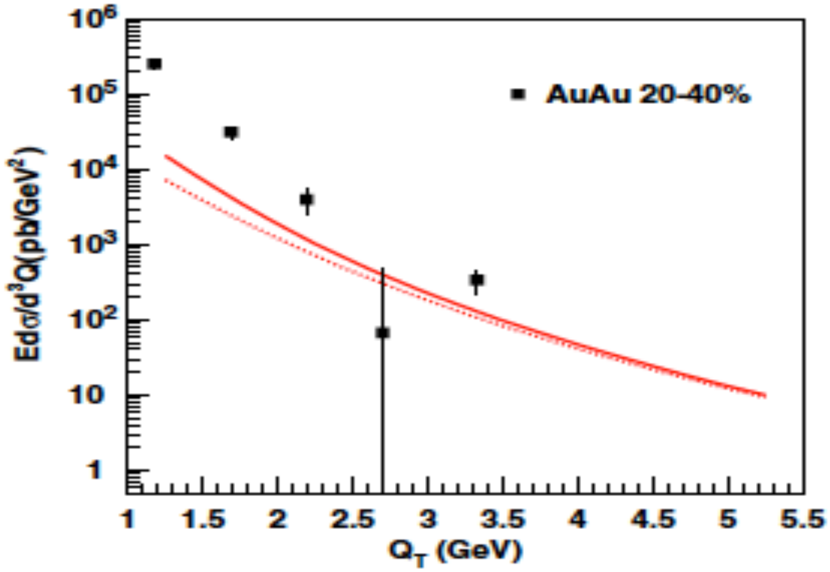


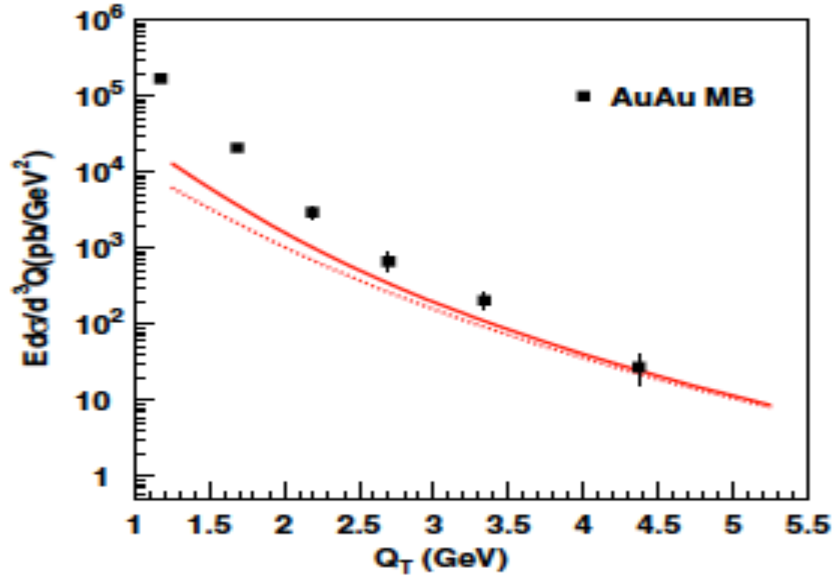


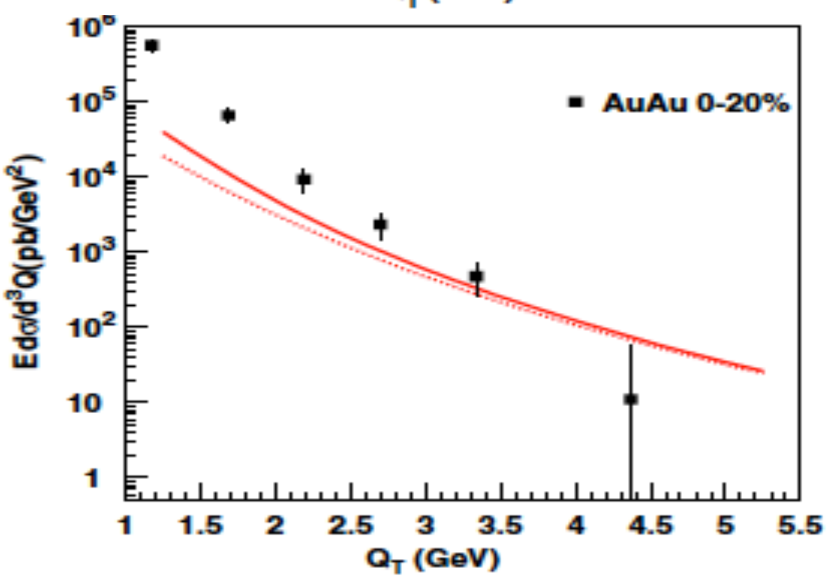
– The band is given by κ=1 (top lines) and κ=0 (bottom lines)

– RAA follows the feature of gluon distribution if turns off isospin

AuAu data: shadowing + isospin only







Data from PHENIX: arXiv:0804.4168

– EPS08 nPDFs

$$\kappa = 1(\text{solid}),\ \ \kappa = 0(\text{dotted})$$

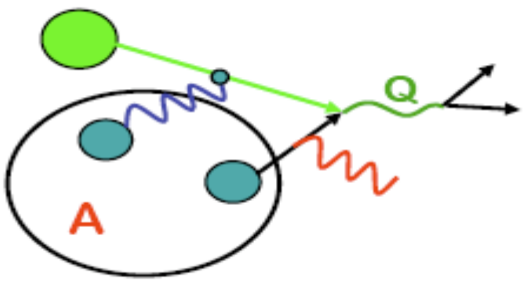
– Clear enhancement at low Q_T

Effect beyond single scattering?

Kang, Qiu, Vogelsang, PRD 2009

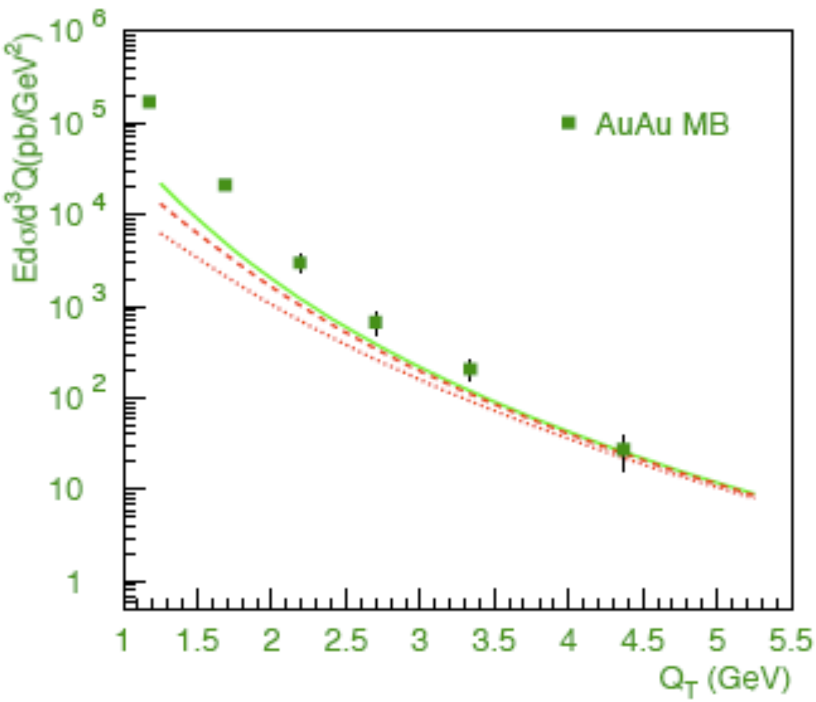
Other nuclear effect: multiple scattering

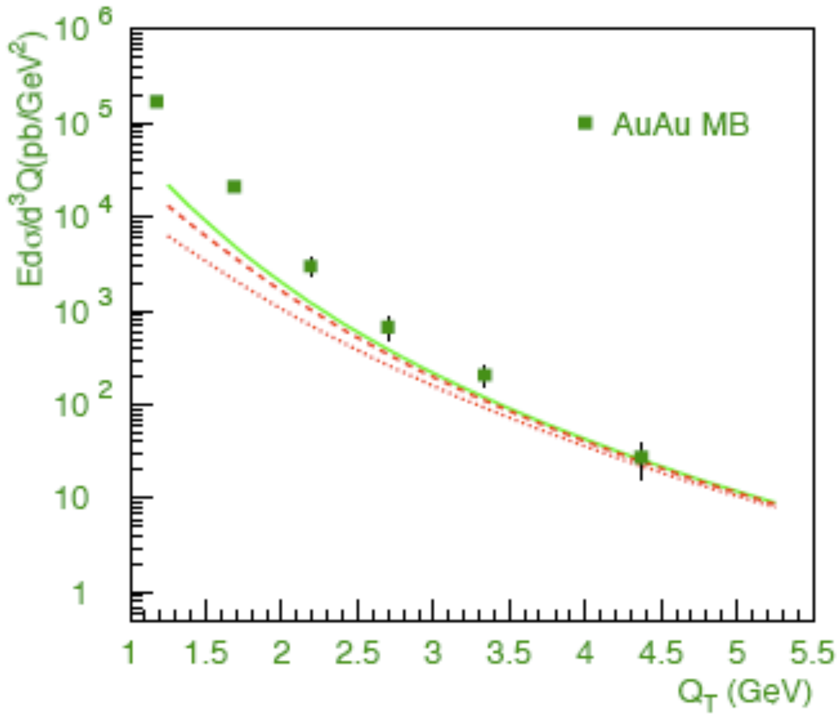
- Initial state multiple scattering – power correction:



Guo, 1998

Unlike DIS, power correction to lepton pair production is positive

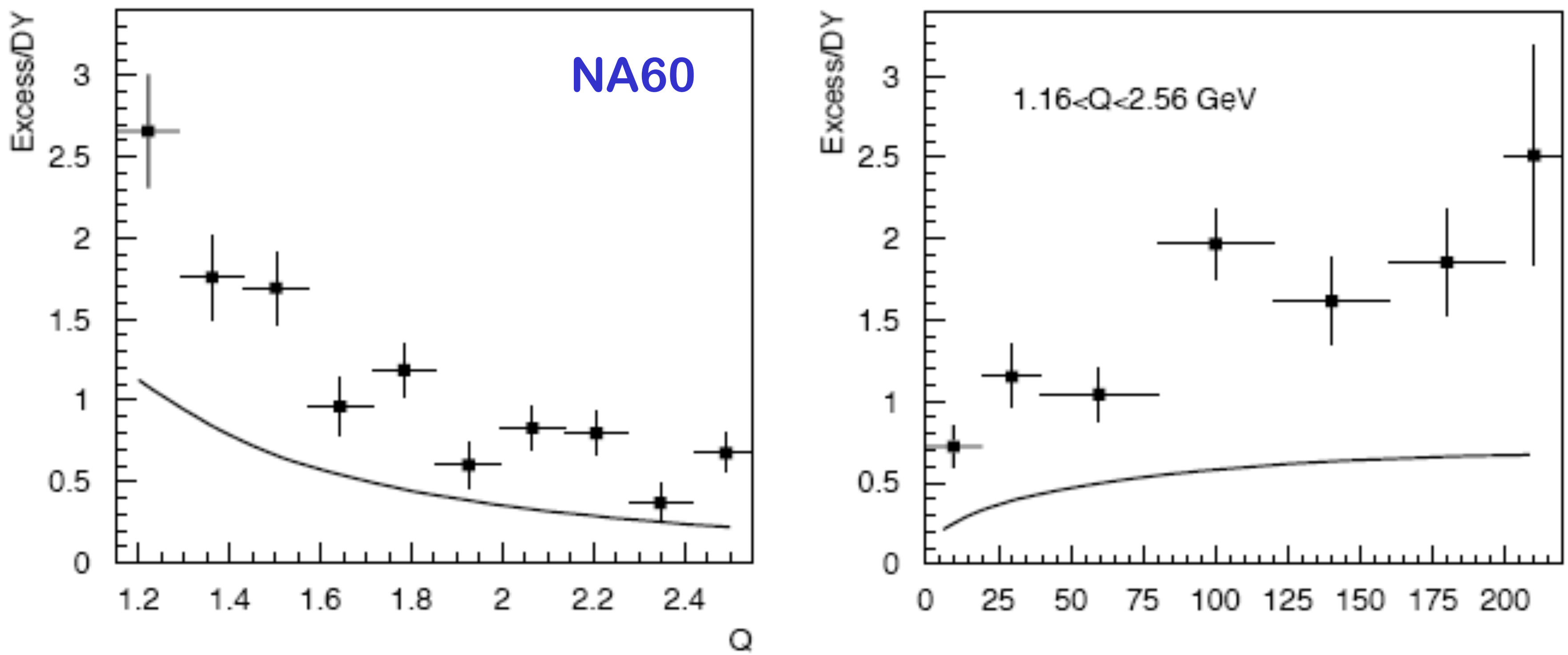




Power correction from cold nuclear matter (solid) is not enough!

Cross check: lepton pair cross section

- Power correction to inclusive total rate: $d\sigma^{AA}/dQ^2$



❖ Power correction from cold nuclear matter is also too small for the enhancement in NA60 data

❖ But, the difference is smaller than that seen in RHIC data

Summary and outlook

- Hadronic production of low mass lepton pairs at high p_T is perturbatively calculable
  - QCD factorization is as good as that for direct photon production
- Low mass lepton pair production is complementary to direct photon production in extracting gluon distribution
  - Cleaner lepton signals, no complication on isolation cut, but, relatively lower rate
- Nuclear enhanced power corrections from cold nuclear matter alone can not explain the observed excess of lepton pair production at low p_T in AuAu collisions:
  - Thermal photons from sQGP, …

Thank you!

Backup transparencies